On solar radius measurements with PICARD

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Introduction

Solar diameter measurements performed from the ground for several decades seem to indicate a relation between the solar diameter and the solar activity. If this relationship is confirmed, it would be possible to use measurements of solar diameter as a proxy of solar activity in the past since the 1715 solar eclipses, and to use this input for the reconstruction of solar irradiance in climate models. However the interpretation of ground observations is controversial, ground-based measurements being affected by refraction, by atmospheric turbulence, and perhaps by atmospheric aerosols scattering. The only way to be free from atmospheric effects is to measure from space. This is the reason why, since the beginning, the PICARD program included a space and a ground component set up at the Calern site of the Observatoire de la Côte d'Azur. During the last 4 years, the PICARD space mission has been used for observing the apparent solar diameter. First results of the astrometry program include a study of the June 2012 Venus transit for solar diameter determination. From this, the value of the solar radius from one astronomical unit was found to be equal to 959.86 arc-seconds. However, concerning observed variations in time of the solar radius, instrumental effects affect the results. Space is known to represent a harsh environment for optical instruments. Nevertheless, we can use the PICARD data to monitor the solar radius variation. PICARD aims to perpetuate historical series of the solar radius measurements, in particular during the solar cycle 24. This poster presents solar radius measurements obtained with PICARD, and the methods developed.

1 – PICARD observations

The PICARD programme owes its name to Jean Picard (1620-1682) who is considered to be a pioneer of modern astrometry. The project involves not only a space mission but also a ground-based observatory at Calern (latitude N43°44'53", longitude E6°55'36", and altitude of 1,271 m). Thus, measurements are taken in orbit by the PICARD mission satellite in order to avoid the impact of atmospheric effects. Nevertheless, it is important to understand and interpret the ground-based measurements, which actually constitute the longest series of currently available measurements. This is why an important ground-based measurement programme ("PICARD SOL") is associated with the space operation before, during, and after the PICARD space mission. One of the main objectives of the PICARD mission is the measurement of the solar diameter during the solar cycle 24.

Measuring with precision the diameter of a gaseous sphere whose envelope is constantly changing represents a seemingly unachievable challenge, especially as the terrestrial atmosphere through which observations are made constitutes an immense handicap. To these difficulties are added the definition of the solar limb, which acts as a geometric reference point to demarcate the solar sphere.

The observations made outside the atmosphere are, in principle, more favourable. However, the space environment (UV effects, radiation, South Atlantic anomaly, thermal cycling, etc.) leads to considerable wear and tear of the instruments in orbit, which observe the Sun directly (combination of the effects of contamination, radiation, temperature variations, and detector responses). All these effects require correction (optical, thermal, electrical, etc.). On the ground, the instruments are far less affected by wear and tear and maintenance is possible. Nevertheless, measurements are affected by the atmosphere and require other types of correction (refraction, turbulence, etc.) that do not make it easy to obtain an absolute measurement of the Sun's diameter and to monitor variations in solar radius.

Figure 1 shows the evolution of variations in solar radii observed at one astronomical unit by the two telescopes of the PICARD mission. We determined the solar radius from the inflection point position (IPP) of solar limb profiles taken at different angular positions of the image.

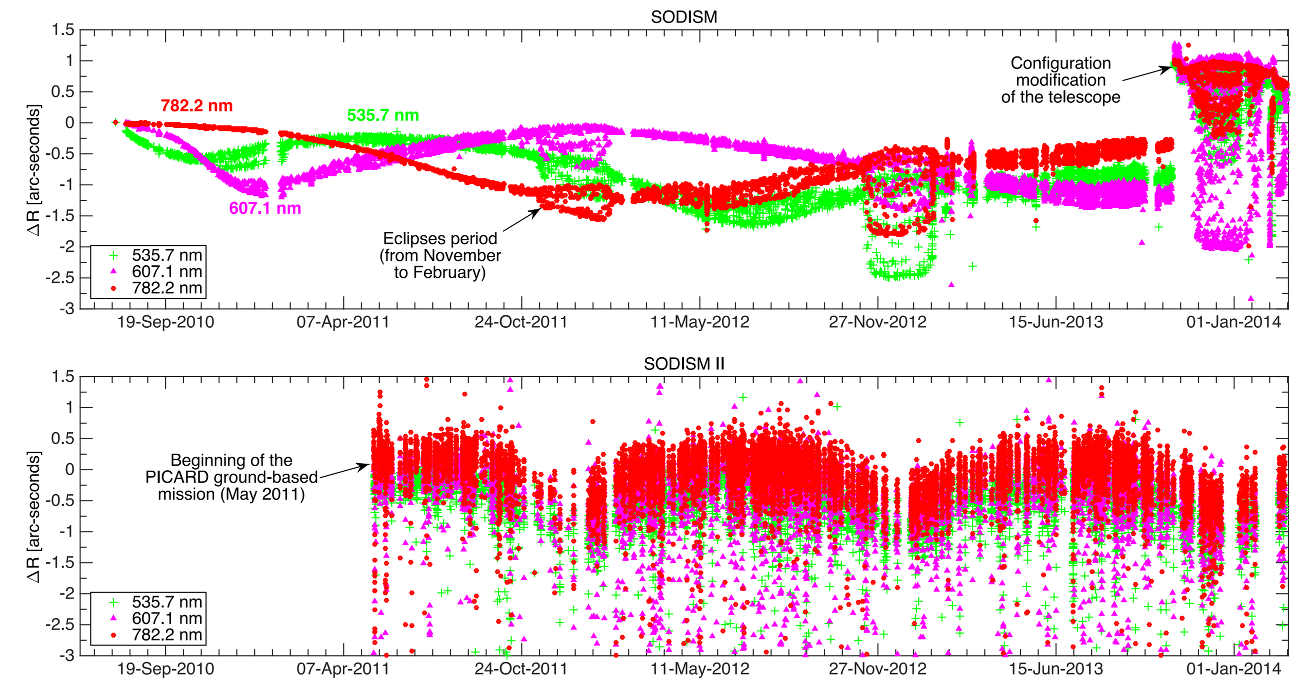


Fig. 1. (Top) Evolution of raw apparent solar radius variability over time (measurements in orbit). This shows the impact of space environment on measurements carried out by the PICARD/SODISM telescope. (Bottom) Evolution of raw apparent solar radius variability over time (measurements on the ground). This shows the impact of atmosphere on measurements carried out by the PICARD/SODISM II telescope.

2 – Models & corrections (space observations)

In orbit at an altitude of 730 km, the PICARD SOlar Diameter Imager and Surface Mapper (SODISM) performed measurements of the Sun's diameter between August 2010 and March 2014 on the basis of an image of our star formed by a Ritchey-Chretien telescope on a charge-coupled device (CCD) detector. In spite of observations outside the atmosphere, we were able to note that the space environment combined with initial defects in telescope calibration (astigmatism, position of the focal plane, etc.) can degrade considerably the measurements taken by our instrument (see measurement obtained with SODISM, Figure 1). Figure 2 shows the long-term evolution in the normalised integrated intensity of images for each wavelength, which highlight the effects of contamination (particularly in the UV). One of the consequences is the change in temperature of the SODISM entrance window during the mission (modification of thermo-optical properties → solar absorption α_f and emissivity ε_{out}).

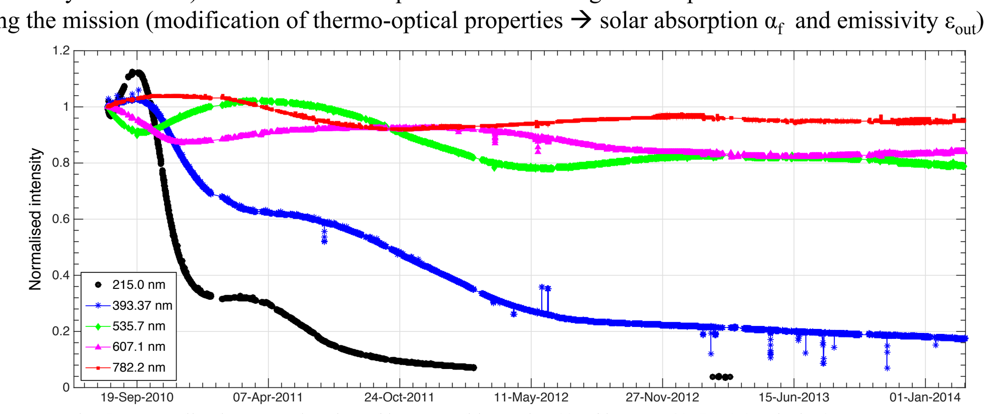


Fig. 2. Normalised temporal series of integrated intensity (I) of images (PICARD mission).

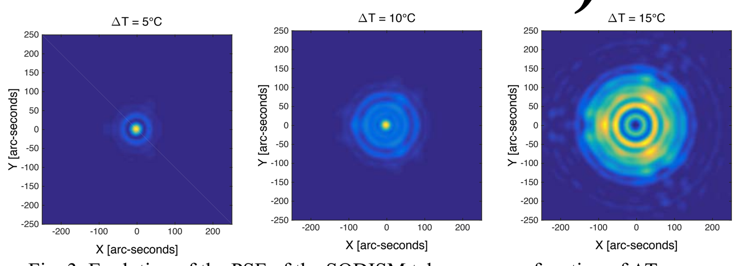


Fig. 3. Evolution of the PSF of the SODISM telescope as a function of ΔT.

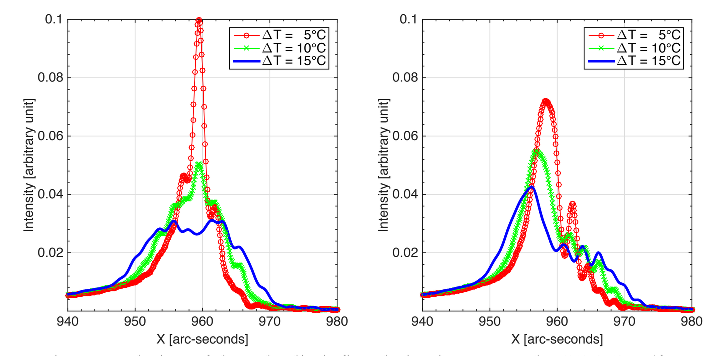


Fig. 4. Evolution of the solar limb first derivative as seen by SODISM (from the LDF of the Sun convolved with the instrument's PSF). (Left) Effect of ΔT. (Right) Effect of ΔT combined with an astigmatism defect.

The various observations we carried out in orbit reveal the usefulness of the models developed for data correction. The temperature of SODISM entrance window T(r) has an impact on solar radius measurements. A temperature gradient (ΔT) in the telescope's entrance window greater than 5°C leads to significant variations in solar radius measurements related to degradation of the telescope's point spread function (PSF) at 782.2 nm (Figure 3). The change in the first derivative of the solar limb darkening function (LDF) at 782.2 nm convolved to the PSF of the instrument is given in Figure 4. These various simulations show the sensitivity of our telescope when it is subjected to a temperature gradient. Finally, evolution of the solar radius as a function of the temperature gradient can be seen in Figure 5 and reveals the dependency with wavelength. Results associated with models are shown in Figure 6.

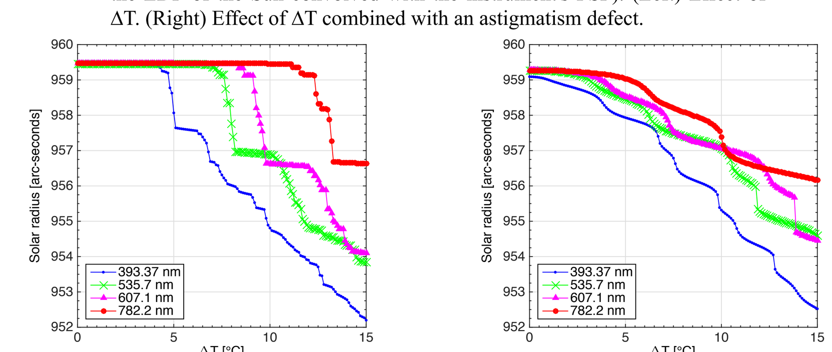
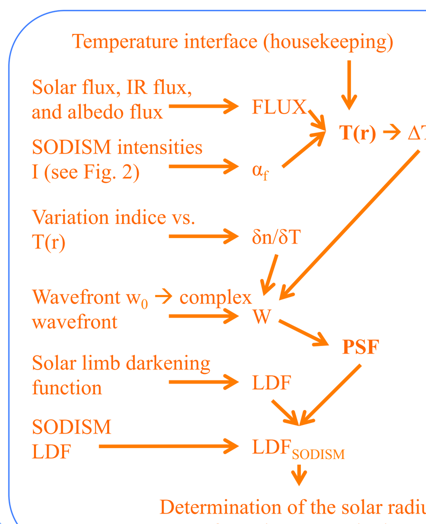


Fig. 5. (Left) Evolution of the solar radius as a function of ΔT. (Right) Effect of ΔT combined with a telescope astigmatism defect on measurement of the solar radius.



Optical model → PSF

$$w_0 = \sum_{k=1}^{36} C_k \times Z_k(\rho, \theta)$$

$$C_3 = \frac{\delta \times D_{PS}^2}{16 \times \lambda \times f_S^2} + \frac{1}{2 \times \lambda} \times \frac{\partial n}{\partial T} \times h_w \times \Delta T(\alpha_f)$$

$$\frac{\partial n}{\partial T} = A_0 + A_1 \times \exp\left(\frac{-\lambda}{B_1}\right) + A_2 \times \exp\left(\frac{-\lambda}{B_2}\right)$$

$$W(p_x, p_y) = A_{DPS} \times e^{2i \times \pi \times w_0}$$

$$PSF_{SODISM}(x, y) = \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} W(p_x, p_y) \times e^{2i \times \pi \times (x \times p_x + y \times p_y)} \, dp_x \, dp_y$$

$$LDF(r_S, \lambda) = \sqrt{1 - r_S^2}^{\,\alpha_S(\lambda)}$$

$$LDF_{SODISM} = \int_{y_1}^{y_2} PSF_{SODISM}(x, y) \, dy * LDF(r_S, \lambda)$$

Thermal model → ΔT

$$T_{it+1}(r) = T_\infty + \frac{Flux}{\varepsilon_{out} \times \sigma \times \overline{T}} + C_1 \times J_0(i \times r \times C) + C_2 \times Y_0(i \times r \times C)$$

$$Flux = \alpha_f \times \varphi_S + \varepsilon_{out} \times fv_{ir} \times \varphi_{IR} + \alpha_f \times fv_a \times \varphi_A$$

$$\overline{T} = (T_\infty + T_{it}(r)) \times (T_\infty^2 + T_{it}(r)^2)$$

$$C = \sqrt{\frac{\varepsilon_{out} \times \sigma \times \overline{T}}{\Lambda \times h_w}}$$

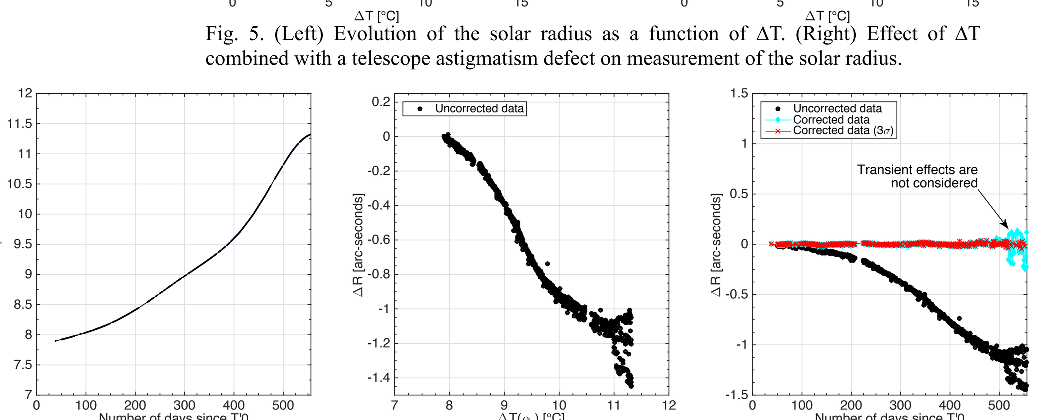


Fig. 6. (Left) Evolution of SODISM entrance widow temperature gradient ΔT (obtained by modelling). (In the middle) Relation between ΔT and uncorrected solar radii at one astronomical unit. (Right) Evolution of the solar radii at one astronomical unit (uncorrected and corrected) since the first measurements carried out by SODISM in August 2010.

4 – Results

SODISM has taken more than one million images of the Sun at several wavelengths. The replica of the space instrument (SODISM II) installed at the Calern site (France) has taken more than 100,000 measurements of the solar radius over a period of more than three years at several wavelengths. Using measurements carried out by instruments on the PICARD mission, we established the variations in the solar radius during the rising phase of cycle 24. Moreover, we also investigated correlations between solar activity, measurements of total solar irradiance, and fluctuations in the radius of our star. The total solar irradiance varies over a number of different timescales ranging from several minutes to several decades (a daily variability can reach peak-to-peak amplitudes of around 0.3%, a variability of around 27 days that is a function of the evolution of sunspots and faculae, a variability of around 11 years with an amplitude in the order of 0.1%, etc.). Could we attribute part of the variations in total solar irradiance to variations in solar radius? The precision of measurements is a critical point that requires space observations to be used since the terrestrial atmosphere constitutes an impediment (see ground measurements obtained with SODISM II, Figure 1). In spite of these observations outside the atmosphere, we were able to note that the space environment (UV effects, contamination, thermal cycling, etc.) combined with initial defects in telescope calibration (astigmatism, position of the focal plane, etc.) can degrade the measurements taken by our instrument considerably (see measurement obtained with SODISM, Figure 1). The various observations we carried out on the ground and in orbit reveal the usefulness of the models developed for data correction (see models and corrections). In addition, we found that images taken at 782.2 nm were relevant both on the ground and in orbit, and this for different reasons (wavefront of ground measurements less subject to phase disruption by turbulence in the higher wavelengths, and impact of temperature gradient of the space telescope window on PSF lower at 782.2 nm). Using measurements we performed on the ground and outside the atmosphere, and on the basis of the models we developed, we can determine the fluctuations in solar radius as a function of solar activity during the rising phase of cycle 24, which makes this one of the smallest sunspot cycle since cycle 14. The solar radius fluctuations observed with the SODISM II instrument at 782.2 nm show variations below +/-50 mas after 40 months of measurement (Figure 9). In early 2014, the observations were disrupted by very bad weather conditions at the Calern site and by the lack of measurements that we were able to take. The trend of our measurements shows an evolution of solar radius below 25 mas (tendency with a non-significant negative slope) during the period 2011-2014, which requires a more detailed analysis (turbulence effects, etc.). Our ground-based observations could not find any direct link between solar activity and fluctuations in solar radius, considering that the variations, if they exist, are included in this range of values. In fact, we find no relationship at all between the change in the number of sunspots and/or total solar irradiance (TSI). Similarly on the basis of measurements taken by SODISM in orbit, we obtain solar radius fluctuations that are below than +/-15 mas (i.e. +/-10.9 km) over the period 2010-2011, and with no direct link to solar activity, considering again that the variations, if they exist, are included in this measurement uncertainty. Thus, we obtain overlapping results between those obtained by SODISM and those obtained by SODISM II.

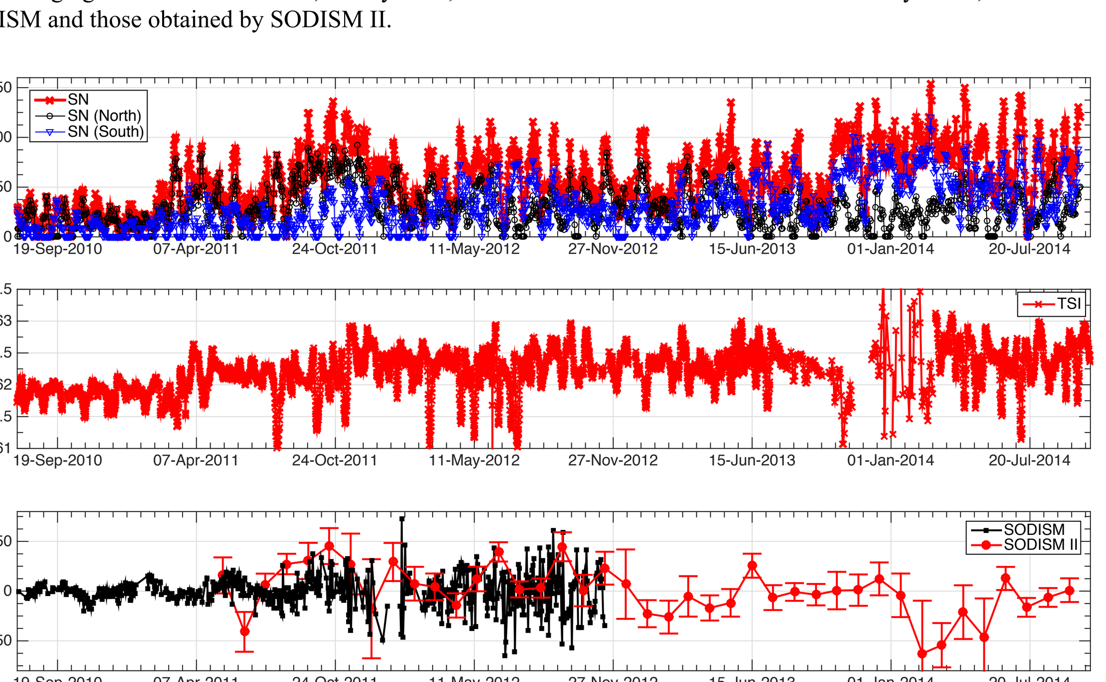
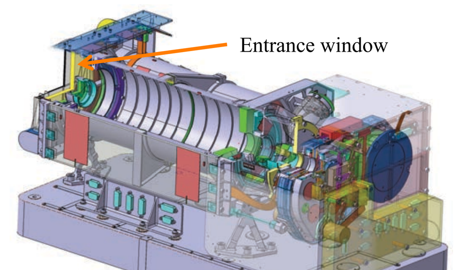
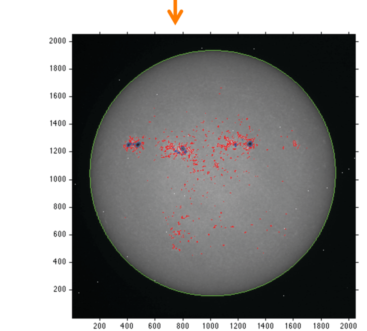


Fig. 9. (Top) Evolution of solar activity characterised by the number of sunspots. (Middle) Evolution of total solar irradiance since August 2010. (Bottom) Evolution of solar radius measured by the SODISM space instrument and by the SODISM II ground instrument.



Computer-aided design representation of the SODISM/SODISM II telescope.



SODISM image at 393.37 nm that can highlights sunspots and faculae.

3 – Models & corrections (ground-based observations)

On the ground (at Calern, France), the SODISM II telescope (replica of the space instrument) has been carrying out complementary solar measurements since May 2011. The main sources of disruption acting on solar images are related to the transparency of the atmosphere and turbulence effects (modifying the apparent mean solar radius up to over 1 arc-second). A turbulence monitor (MISOLFA or Moniteur d'Image SOLaire Franco-Algérien) was developed in order to characterise atmospheric turbulence. In addition, the data have to be corrected for astronomical refraction.

Astronomical refraction influences the solar radius measurements (more than 1 arc-second for observations made above 70° of zenith distance z) that we obtain from images taken with SODISM II. We therefore use a numerical method to correct mean solar radius measurements at whatever wavelength (λ). This correction also depends on air temperature (T_a), pressure (P_a), and relative humidity (f_h). An approximate formula for correction is used, which shows the relationship between the corrected solar radius for refraction (R_{cor}), the observed solar radius (R_{obs}), and the refraction correction coefficient (C_{ref}). α_r is the air refractivity for local atmospheric conditions at a given wavelength (see Ciddor, 1996), and β is the ratio between the height of the equivalent homogeneous atmosphere and the Earth radius of curvature at observer position assuming ideal gas law for dry air (see Corbard et al., "Astronomical refraction correction for ground-based full disk solar astrometry", Solar metrology needs and methods, Paris, October 7-9 2014).

$$R_{cor} \simeq R_{obs} \times (C_{ref}(T_a, P_a, f_h, \lambda, z))^{-1}$$

$$C_{ref}(T_a, P_a, f_h, \lambda, z) = 1 - k(T_a, P_a, f_h, \lambda) \times (1 + 0.5 \times tan^2(z))$$

$$k(T_a, P_a, f_h, \lambda) = \alpha_r(T_a, P_a, f_h, \lambda) \times (1 - \beta(T_a))$$

When an optical measurement is carried out on the ground, the photons originating from a source such as the Sun undergo diffusion effect by molecules in the atmosphere and turbulence effect. These effects lead to spread the solar limb and affect the position of its inflection point as well as its variability. Turbulence represents the main source of uncertainty in the measurements we carry out using SODISM II. One of the objectives of the MISOLFA instrument is to quantify the effects of atmospheric turbulence on measurements of solar diameter carried out by SODISM II. The change in full width at half maximum (FWHM) of the first derivative of the solar limb observed by SODISM II (Figure 7) can also be used as a relative indicator of turbulence given the relationship between the FWHM and the pupil diameter of the telescope. The results presented in Figure 8 were obtained from images acquired at 782.2 nm. Corrected data are obtained using the correction models (for refraction but not for turbulence).

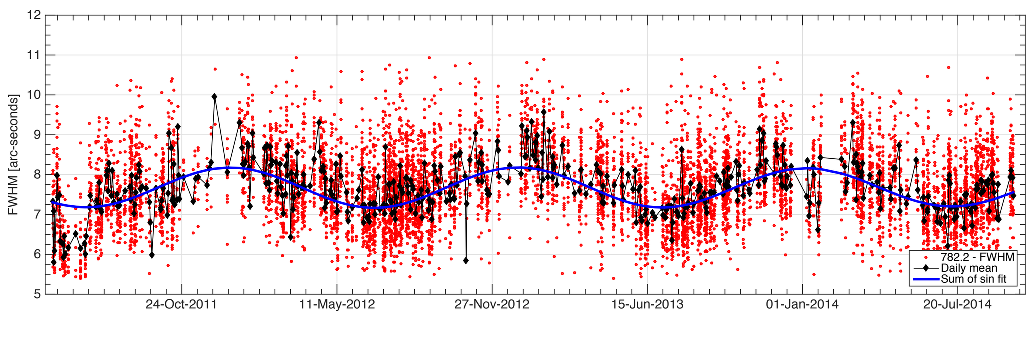


Fig. 7. Evolution of full width at half maximum (FWHM) of the solar limb first derivative observed by the SODISM II instrument at 782.2 nm.

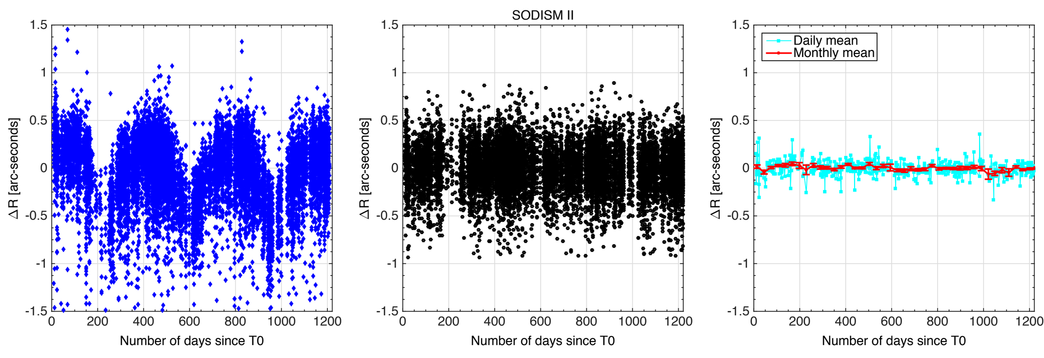


Fig. 8. (Left) Evolution of the solar radii at one astronomical unit (uncorrected and corrected data for refraction with mean value of k) since the first measurements carried out by SODISM II in May 2011.

Conclusion

The measurements taken by instruments on board the PICARD satellite were completed by ground-based measurements and this has made it possible to understand and model the disruptive effect of the Earth's atmosphere on observations of the Sun made from the ground. Among the ground-based instruments, a replica of the SODISM imaging telescope coupled to a MISOLFA turbulence monitor were and continue to be used. Measurements performed by instruments on the PICARD mission have allowed us to establish evolution of the solar radius during the rising phase of solar cycle 24. It highlights the complementarity of the measurements made on ground and outside the atmosphere. For this, we developed specific methods in order to correct the various measurements. Fluctuations in the solar radius observed with the SODISM II instrument show variations below +/-50 mas after 40 months of measurement. Ground based measurements over the period 2011-2014 show a non-significant trend. This remaining trend uncertainty requires a more detailed analysis. Our ground-based observations could not find any direct link between solar activity and fluctuations in solar radius, considering that the variations, if they exist, are included in this measurement uncertainty. Similarly, on the basis of measurements carried out by SODISM in orbit, we obtain fluctuations in the solar radius that are below +/-15 mas (that is +/-10.9 km) during the period 2010 to 2011. Our space observations could not find any direct link between solar activity and fluctuations in solar radius. Thus, we were able to confirm, from the measurements we made, that the contribution of solar radius fluctuations is low with regard to variations in total solar irradiance. However, we must continue our ground-based measurements to better quantify these variations during this very particular solar cycle.

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